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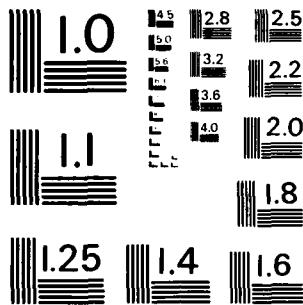
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CHEMICALLY REACTING TURBULENT SHEAR LAYERS

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Abstract

An experimental investigation of entrainment, mixing and chemical reactions in a plane shear layer has been performed using laser induced fluorescence techniques. Results indicate that the reactants mix on a molecular level and react at a composition that is nearly uniform across the width of the layer. The composition of the mixed fluid is found to be asymmetric, with an excess of high speed fluid, suggesting that entrainment into the shear layer is asymmetric. These results are at variance with predictions of models based on gradient transport and eddy diffusivity.

Introduction

Experimental investigations in recent years¹⁻⁴ suggest that entrainment and mixing processes in turbulent shear layers are dominated by the dynamics of large scale vortical structures. The evidence suggests that pure fluid entrained from the free streams can be transported unmixed across the whole transverse extent of the shear layer and that, in the case of chemical reactions between the entrained fluids, the chemical product is found in regions associated with the large vortical structures. This view of the turbulent entrainment and mixing process is in contradiction with prevailing views of these phenomena based on concepts of gradient transport and eddy diffusivity, which model the mass transport into and across the turbulent layer as a diffusive process, whose flux is proportional to the local mean concentration gradient.

In order to investigate these phenomena further, the mixing and chemical reaction processes in a two-dimensional shear layer were studied. Employing laser induced fluorescence and a pH sensitive fluorescent dye, the local chemical environment was monitored in a shear layer formed between acid and base bearing free streams.

Experimental Apparatus and Measurements

The shear layer was produced in a small blow-down facility, in which the chemical composition of each of the two free streams could be prepared to any concentration. A gaseous nitrogen supply system, regulated through separate sonic orifice metering valves, maintained the free stream flow velocities nearly constant. Transients and possible U-tube oscillations were minimized by placing two large ballast vessels in the gas supply route, whose effective capacitance in conjunction with the resistance in the supply

tubes, allowed for adequate damping of the whole system (see Fig. 1).

An acid-base reaction was used, with the fluorescent dye premixed with the acid solution. The dye was sodium fluorescein which fluoresces efficiently, when excited by an argon ion laser, provided it is in a chemical environment whose pH is above a certain threshold. Since the fluorescence of this dye can be quenched in an acid environment, the fraction of the mixed fluid whose pH was above this threshold could be readily monitored. Note that this corresponds to mixed fluid containing an excess of base. The equivalence ratio of the free streams, defined here as the volume of high speed fluid required to titrate a unit volume of low speed fluid and cross the pH fluorescence threshold of the dye, could be set to any value. The fluorescence on/off transition was very sharp (of the order of one part per mil) based on the mixture volume ratio, for the concentrations that were used in this experiment. Note that since the fluorescence behavior of this dye depends on its local chemical environment, this diagnostic permits measurements of the composition of the mixed fluid down to the molecular scale.

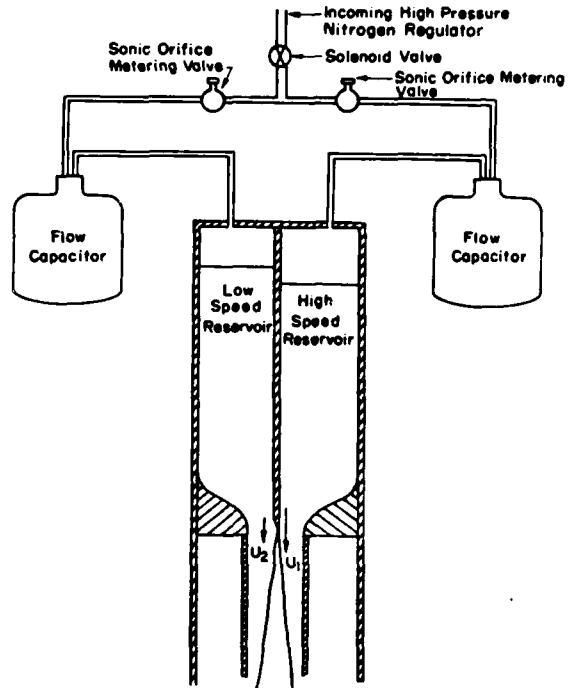


Fig. 1. Mixing layer flow facility.

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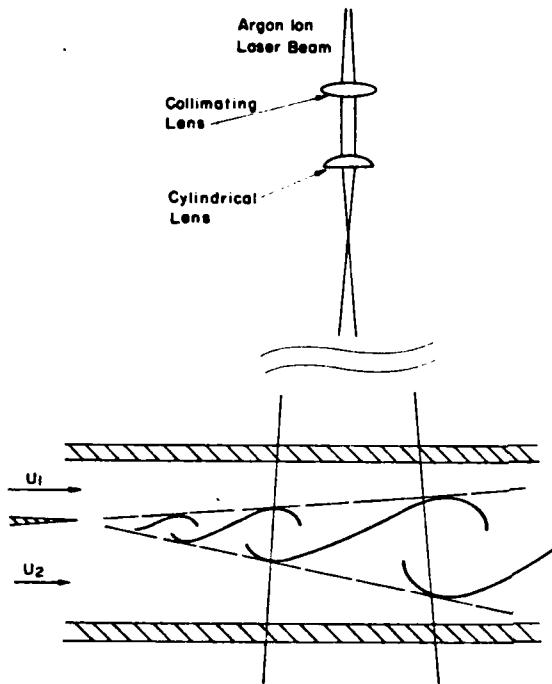


Fig. 2. Optical layout.

A 3W argon ion laser (Coherent Radiation CR-3) beam was passed through a combination of spherical and cylindrical optics to produce a sheet, about 1 mm in thickness, illuminating a portion of the test section (see Fig. 2). A motor driven 35 mm camera was used to photograph the resulting fluorescent chemical product on normally developed Kodak TRI-X film.

For the experiments reported here, the concentrations of the base and acid solutions in the free streams were selected in such a way so as to require 1.8 part of the basic solution to titrate one part of the acid solution. The free stream velocities were set with $U_1 = 42$ cm/sec on the high speed side, and a low speed side corresponding to a velocity ratio $U_1/U_2 = 2.2$. Both solutions were sufficiently dilute, so that the resulting densities were essentially equal to that of water. Two sets of runs were made under identical flow conditions and optical setup. In the first set of measurements, the acid solution was placed on the high speed side with the base on the low speed side. For the second set, the chemicals were reversed. Typical results are shown on figure 3. The visible portion of the apparatus in the photographs corresponds to a downstream region of $12.5 \text{ cm} < x < 22.5 \text{ cm}$, as measured from the tip of the shear layer splitter plate, and a Reynolds number range of $1940 < \text{Re} < 3490$, based on the velocity difference and the local vorticity thickness. The test section width is 3.5 cm with a span of 23.5 cm.



(a)



(b)

Fig. 3. Photograph of chemical reaction in a shear layer ($f/1.8$, 2 msec exposure), high speed stream on top with $U_1 = 42$ cm/sec and $U_1/U_2 = 2.2$, flow from left to right.
 a. acid on the high speed side and base on the low speed side,
 b. base on the high speed side and acid on the low speed side.

Results and Discussion

Based on the properties of photographic film (TRI-X), the amount of chemical product, defined here operationally as the fraction of the fluid whose pH is in excess of the fluorescence threshold can be estimated. Approximately two orders of magnitude difference in the amount of product can be found between the two cases in the photographs depicted in figure 3.

It should be pointed out that no gradient transport model that we are aware of can account for this very large difference in behavior. Figure 4 is a sketch of the expected results for this experiment, based on the gradient diffusion transport model. The mean concentration profiles of the two reactants (in the absence of a chemical reaction) and the mean concentration of product are indicated. Note that the product mean concentration profile was drawn for an acid-base (reversible) chemical reaction that proceeds

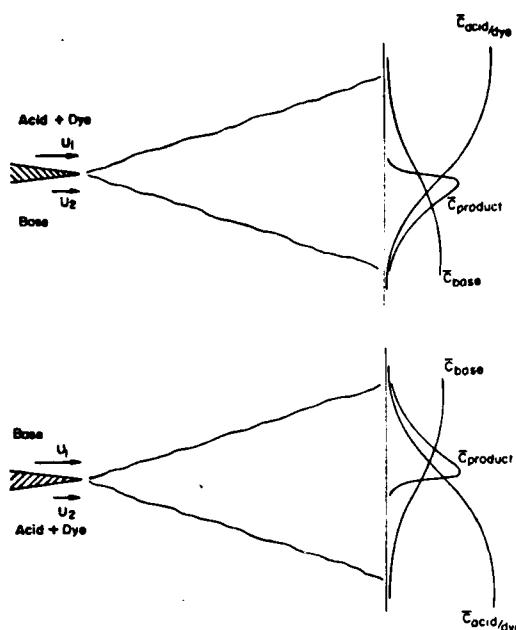


Fig. 4. Schematic of the expected mean product concentration profile based on gradient diffusion model.

when the reactants are mixed with an excess of base. Strictly speaking, if the model does not accommodate fluctuations in the concentration of the reacting species, the resulting product profile would be found to possess a sharp cut-off. The effect of fluctuations would be to round off these sharp edges. This is indicated symbolically in figure 4. Note also that these models would necessarily predict a range of compositions of the mixed fluid, which is centered around the local value of the mean. Consequently, the models would predict approximately the same amount of product for the two cases in our experiment.

The results can perhaps be understood in part in terms of a simple mixing model, proposed recently by Broadwell and Breidenthal⁵. According to this model, the shear layer entrains a certain ratio of high speed fluid to low speed fluid, which as suggested by the work of Konrad⁴, need not be unity. The entrained fluid from the two sides of the shear layer mixes and homogenizes at a composition corresponding to this entrainment ratio. In addition, there are contributions from the strained 'flame sheets' between the two fluids, which in the case of liquids (high Schmidt number), would be small.

In our experiment, the predominant fraction of the mixed fluid in the top photograph of figure 3 can be seen to be at a composition below the threshold value required to turn the fluorescence on. When the base is placed on the high speed side, however, the predominant composition of the mixed fluid is such that it crosses the fluorescence threshold. This supports the asymmetric entrainment into the layer, described by Konrad⁴. Note that the lack of any

significant fluorescence intensity variation in the bottom photograph of figure 3 implies a fairly uniform composition of the mixed fluid.

Conclusions

Investigations into the nature of mixing and chemical reaction in a plane shear layer suggest that these processes are not described adequately by models based on concepts of gradient transport and eddy diffusivity. The composition of the mixed fluid was found to be nearly uniform across the width of the mixing layer. This composition was biased in favor of the high speed fluid, implying that the entrainment into the shear layer is asymmetric.

Acknowledgements

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